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The Use of β Titanium Alloys in the Aerospace Industry

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Beta titanium alloys have been available since the 1950s (Ti-13V-11Cr-3Mo or B120VCA), but significant applications of these alloys, beyond the SR-71 Blackbird, have been slow in coming. The next significant usage of a β alloy did not occur until the mid-1980s on the B-1B bomber. This aircraft used Ti-15V-3Cr-3Al-3Sn sheet due to its capability for strip rolling, improved formability, and higher strength than Ti-6Al-4V. The next major usage was on a commercial aircraft, the Boeing 777, which made extensive use of Ti-10V-2Fe-3Al high-strength forgings. Ti-15V-3Cr-3Al-3Sn environmental control system ducting, castings, and springs were also used, along with Ti-3Al-8V-6Cr-4Mo-4Zr (β-C) springs. Beta-21S was also introduced for high-temperature usage. More recent work at Boeing has focused on the development of Ti-5Al-5Mo-5V-3Cr, a high-strength alloy that can be used at higher strength than Ti-10V-2Fe-3Al and is much more robust; it has a much wider, or friendlier, processing window. This, along with additional studies at Boeing, and from within the aerospace industry in general will be discussed in detail, summarizing applications and the rationale for the selection of this alloy system for aerospace applications.

Keywords forgings, Ti-10V-2Fe-3Al, Ti-5Al-5Mo-5V-3Cr

1. Introduction

A generally accepted definition of a β alloy would be one with enough total β stabilizer content to retain 100% β phase upon quenching from above the β transus. Beta- and heavily β-stabilized α/β alloys offer potential advantages for providing higher tensile and fatigue strengths, the ability to heat treat greater section thicknesses to high strength, easier fabrication into some semiproducts, such as a sheet-type product that is strip-producible, and enhanced formability. The disadvantages of this alloy system would include: a greater possibility of segregation than would be encountered during the melting of an α/β alloy; damage-tolerant-type applications are not normally considered due to crack growth and toughness characteristics; alloys may be difficult to weld (Ti-15V-3Cr-3Al-3Sn has good weldability, but the fatigue properties of the weldment are not attractive); and, due to the fact that alloys such as Ti-15V-3Cr-3Al-3Sn exhibit almost no work hardening, such alloys can be troublesome to form into complex shapes. These attributes limit the applications of β alloys. However, there are still many applications where their use offers performance or fabrication advantages.

2. Brief History

As mentioned previously, the first application of a β alloy was on the Lockheed SR-71 Blackbird in the early to mid-1960s (Ref 1). This aircraft was the first, and is still the "premier" user of β alloys; in fact, it is still the premier user of titanium. About 93% of this aircraft was fabricated from titanium, with most of it being the β alloy, Ti-13V-11Cr-3Mo, which is also known as B120VCA. It is a difficult alloy to work with, both from a melting and component fabrication standpoint, but B120VCA was really the only alloy suitable for this application in that time frame due to its high strength and thermal stability. Forgings had a minimum tensile strength of 1170 MPa (170 ksi) with a minimum elongation requirement of only 2%. Needless to say, designers of this era would tell us that alloys such as that could not be used for critical aircraft applications.

In approximately 1970, McDonnell Douglas began using the first titanium springs on commercial aircraft, which were fabricated from Ti-13V-11Cr-3Al. They were introduced on the DC-10 (Ref 2). Their use then spread to other McDonnell Douglas aircraft, but the volume was small.

Beta alloys were not used again in significant amounts until the North American Rockwell B-1B bomber in the early to mid-1980s. Over 250 parts per ship were fabricated from Ti-15V-3Cr-3Al-3Sn sheet. This alloy was selected for two reasons: it was strip producible, which meant a lower cost than that for Ti-6Al-4V sheet in thin gages; and, at least for simple forming operations, it had superior formability to that of Ti-6Al-4V. In addition, it could be heat treated to tensile strengths of 1034 MPa (150 ksi) and higher. It was used extensively in the nacelles and to form sine-wave spars for the empennage. This sine-wave spar structure is illustrated in Fig. 1.

The next noteworthy application of β alloys did not occur until the early 1990s on the Boeing 777. The most extensive application is in Ti-10V-2Fe-3Al high-strength forgings (minimum ultimate tensile strength [UTS] of 1193 MPa [173 ksi]), with the major application being landing gear structure (Ref 1). This resulted in hundreds of kilograms of weight savings in replacement of high-strength low-alloy (HSLA) steel (4340 or 300 M). Airbus also used this alloy for similar applications (upper links, struts, and truck beams) on their A340-500/600 landing gear (Ref 3). It is understood that they used it at the same strength level.

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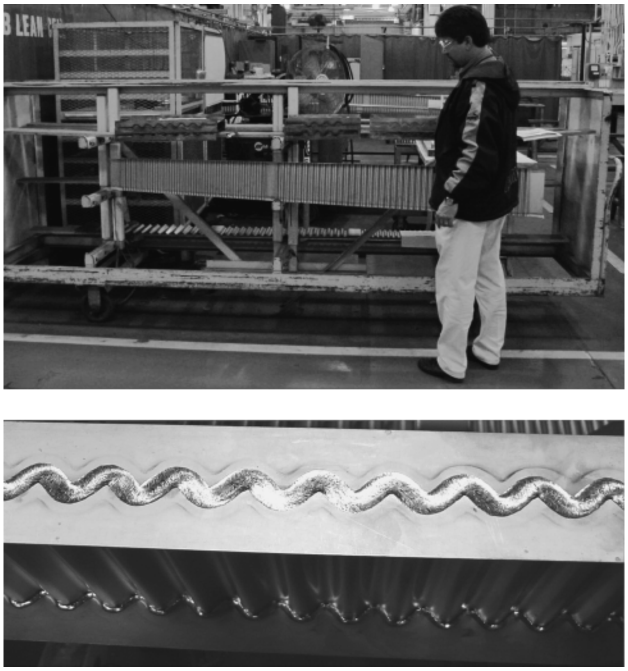

Fig. 1 Sine-wave spar structure fabricated from Ti-15V-3Cr-3Al-3Sn strip used on the B-1B bomber empennage

The Boeing 777 also used formed Ti-15V-3Cr-3Al-3Sn sheet in applications such as environmental control system ducting, clips and brackets, and floor support structure. Ti-3Al-8V-6Cr-4Mo-4Zr (β-C) and Ti-15V-3Cr-3Al-3Sn were used for springs, the former for coil-type springs at a minimum UTS of 1240 MPa (180 ksi) and the latter for clock-type springs with a minimum UTS of 1034 MPa (150 ksi). A few Ti-15V-3Cr-3Al-3Sn castings were also used on this aircraft at the 1138 MPa (165 ksi) strength level. (Some Ti-10V-2Fe-3Al forgings and β alloy springs were used on earlier Boeing aircraft, but the applications were limited.) Another relatively new β alloy, β-21S (Ti-14.7Mo-2.7Nb-3Al-0.27Si) was introduced on the Boeing 777 for high-temperature applications. This was unusual in that β alloys are not normally suited for high-temperature service due to their poor oxidation resistance and creep behavior. However, this particular alloy has excellent oxidation resistance with creep properties comparable to that of Ti-6Al-4V (though not as good as Ti-6Al-2Sn-4Zr-2Mo), and it is resistant to attack by thermally decomposed hydraulic fluid, the only titanium alloy that has been identified to date with this attribute. The exact mix of the various alloys is difficult to trace, but it is thought that the Boeing 777 is the first aircraft, with the exception of the SR-71, in which Ti-6Al-4V was not the dominant alloy. There were, for instance, over 200 Ti-10V-2Fe-3Al part numbers on the Boeing 777. The above-mentioned β alloys were eventually used by other aircraft manufacturers, though not in major amounts. These applications were all driven by weight reduction/improved performance. Life cycle cost advantages also come into play for applications such as springs, where the previously used piano wire steel springs were constant maintenance problems due to corrosion. Life cycle costs are also an advantage for Ti-10V-2Fe-3Al forging applications on the landing gear. Corrosion problems are an issue here as well, and the landing gear is refurbished every 6 to 10 years to handle the corrosion of the HSLA landing gear components. This refurbishment, which has a high associated cost, will not be necessary for Ti landing gear components.

It was previously reported that Ti-10V-2Fe-3Al was being studied for rotating applications on the mast of the Westland Lynx helicopter (Ref 1). Those forgings have in fact been implemented (disc, sleeve, and mast forgings). The rationale for using Ti-10V-2Fe-3Al in place of Ti-6Al-4V was a result of the improved fatigue performance. An extensive thermomechanical processing study was conducted by Westland and Otto Fuchs, including billet processing by TIMET, which resulted in a more robust process, an improved homogeneity of properties, and optimized fatigue strength (Ref 4).

The other place where β alloys, or in this case, β-rich α/β alloys, which are included in this symposium, are used extensively is in Russia and the former Soviet Union (Ref 1). They have made extensive use of an alloy referred to as VT-22 or BT-22, which is nominally Ti-5Al-5Mo-5V-1Fe-1Cr developed at VIAM, the All-Russia Institute of Aviation Materials. This alloy is used extensively in landing gear and other applications by their aircraft manufacturers. It is highly weldable; many of the landing gear components were weldments.

3. More Recent Applications

Springs will be discussed first, as this is an application that is being used by about all aircraft manufacturers and in fact has even spread, in limited applications, to the automobile and other industries, as was discussed to a greater extent by Pepka (Ref 5) in this symposium. Titanium is an ideal material for spring applications with its high strength, low modulus, low density, and excellent corrosion resistance. The low modulus and density in conjunction with the strength enables the use of springs that use half the volume of steel springs (only half the number of coils are required) with weight reductions of up to 70% relative to the steel springs (Fig. 2) (Ref 5, 6). In addition, the previously mentioned corrosion problem with steel springs is eliminated. Typical airframe applications would include up-lock and down-lock springs on the landing gear, door counterbalance springs, flight control springs to control limits and overrides, feel and centering springs for the yoke, pedal returns (brakes), and hydraulic return springs.

Titanium springs are also being used by some of the commuter or regional aircraft original equipment manufacturers (OEMs). The Bombardier uses β-C springs for the up-lock and down-lock springs on their regional jets. For the most part, springs seem to be the extent of β alloy usage for these aircraft. The Cessna jet fleet utilizes Ti-15V-3Cr-3Al-3Sn clock-type springs to assist in the deployment/retraction of the doors/fold-out stairs. Embraer is using the B120VCA alloy at 1380 MPa (200 ksi) minimum tensile strength for torsion bars on their 70-passenger 170 model. It is believed that they also use them on their 90-passenger aircraft.

Forgings of Ti-10V-2Fe-3Al are being used more and more by the aerospace industry. Helicopters built both in Europe (as discussed above) and the United States are utilizing them, though with different processing and strength levels than those used at Boeing. They have reduced the strength to optimize fatigue performance. In Europe, the alloy is used with a minimum ultimate tensile strength of 1100 MPa (160 ksi), resulting in a smooth high-cycle fatigue strength of 650 MPa (94 ksi) at an R ratio ($\sigma_{min}/\sigma_{max}$) of −1.

Fig. 2 The titanium spring on the left carries the same load as the steel spring on the right. Wire gages are the same. The steel spring weighs 4.35 kg, while the Ti spring weighs 1.45 kg.

In the United States, the Sikorsky/Boeing team used Ti-10V-2Fe-3Al on the Comanche for many of the significant components on the main rotor system: for instance, the hub, the structure that holds the rotor system to the airframe, and linkages. (Unfortunately, there were only two of them built before the program was canceled; the Ti-10V-2Fe-3Al parts functioned as expected during the test flights.) They also used this alloy at the 1100 MPa tensile strength level to replace Ti-6Al-4V with the associated weight savings. These savings will be discussed further by other authors in this symposium (Ref 7).

The only regional jet OEM that the authors could find that was using Ti-10V-2Fe-3Al was Embraer, which is using Ti-10V-2Fe-3Al forgings for flap tracks on their 70-passenger 170 model. They have three different part numbers for this application, all of which are produced with a minimum ultimate tensile strength of 1100 MPa (160 ksi). Indications are that it is also used for a similar application on their 190-passenger regional jet.

Beta alloys are generally not used on military aircraft with their heavy emphasis on fracture critical-type designs. The F/A-22 does use some Ti-10V-2Fe-3Al forgings at the 1240 MPa strength level for some arrestor hook structure applications.

4. Future Applications

The Airbus A-380 is utilizing Ti-10V-2Fe-3Al for several main landing gear applications such as the bogie beam, lower and upper torque links, the side stays, and the top and front panels. They are using Ti-10V-2Fe-3Al plate as well as forgings, all at the 1190 MPa (173 ksi) strength level (Ref 3). Ti-10V-2Fe-3Al plate will be used both on the landing gear and for a spoiler fitting.

A sine-wave spar structure similar to that used on the B-1B bomber (Fig. 1) is under consideration for the empennage of the new Boeing 7E7. The strip producibility of the Ti-15V-3Cr-3Al-3Sn is a factor here in that sheet length will not be a limiting factor.

The high-strength titanium forging alloy for the 7E7 will be Ti-5Al-5Mo-3Cr (Ti-5553), in place of Ti-10V-2Fe-3Al. There are several reasons for the use of this alloy in place of Ti-10V-2Fe-3Al. First, the processing window of Ti-10V-2Fe-3Al used at the high-strength level is quite narrow. The primary forging is done above the β transus, which is followed by, nominally, about 15% α/β forging to achieve the right balance among strength, ductility, and toughness. The primary α phase formed during cooling from the β forging temperature has a lamellar morphology, which promotes good fracture toughness but results in low ductility. In addition, extensive grain boundary α will also form, which can further degrade the ductility, particularly with a large grain size. The α/β forging step will recrystallize some of the primary α and break up the grain boundary α, improving the ductility at the expense of fracture toughness. If greater amounts of α/β work are imparted, the ductility will continue to improve, but the fracture toughness will drop to an unacceptable level (Ref 8). Processing will be much simpler for the Ti-5553 alloy; it will be all α/β worked. In addition, it can be solution treated in section sizes up to 152 mm (6 in.) followed by air cooling with only a slight drop in properties at the thicker section sizes, whereas Ti-10V-2Fe-3Al requires a water quench and the section size is limited to 76 mm (3 in.) at the time of heat treatment. Finally, the Ti-5553 can be heat treated to a higher strength, with a minimum tensile strength of 1240 MPa (180 ksi) as opposed to the 1192 MPa (173 ksi) for Ti-10V-2Fe-3Al (Ref 9). At this stage, the Ti-5553 alloy is slated as bill-of-material for landing gear components on the Boeing 7E7. It will not be used quite as extensively as on the 777; the bogie beam will be Ti-5Al-5V-5Mo-3Cr. More extensive use throughout the aircraft is anticipated as design details become clearer.

The alloy was developed in a joint effort between Boeing and VSMPO, the major Russian titanium producer. It is a derivative of their VT-22 alloy. The goal was the development of a modification of the alloy that would have deeper hardenability and would be capable of higher strength.

Boeing is also working on a more durability/damage-tolerant heat treatment of the Ti-5553 alloy for 7E7 applications. A β anneal will be used with a controlled cooling rate followed by an aging treatment. Preliminary data indicate that this lower-strength version is anticipated to have a minimum tensile strength of 1100 MPa (160 ksi) with a minimum fracture toughness of 77 MPa√m as opposed to a minimum value of 33 MPa√m for the high-strength heat treatment. This lower-strength version is being studied for applications in the nacelles, fuselage, and wing.

These Ti-5553 applications are driven by improved performance and weight reduction. Other applications under consideration would take advantage of this and the corrosion compatibility of titanium with the graphite fibers in the carbon fiber-reinforced plastic structure. While aluminum structure will be used where it can due to its lower cost, and, often, lower

Table 1 Ti-5553 room temperature static tensile properties compared to Ti-6Al-4V typicals (19 mm section size) (Ref 11)

Property	Cast and HIP'ed Ti-5553	Cast and HIP'ed Ti-64
UTS, MPa	1159	910
YS, MPa	1055	828
El, %	9	8.9
Compressive YS, MPa	1138	897
Max shear, MPa	690	655
Bearing UTS (*E*/*d* = 2.0), MPa	2248	1862
Bearing YS (*E*/*d* = 2.0), MPa	1931	1648

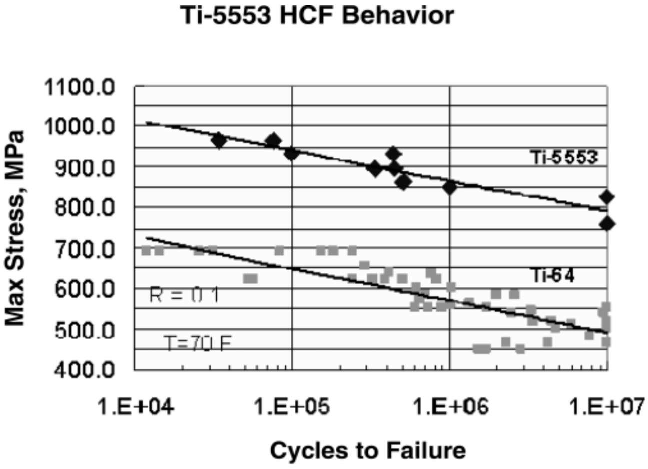

Fig. 3 HCF characteristics of Ti-5553 Alloy (HIP + heat treated) compared with cast Ti-64 (HIP + mill anneal) (Ref 11). (Note: HCF, high cycle fatigue; HIP, hot isostatic press)

weight, titanium will be used for critical applications in corrosion-prone areas that are difficult to inspect and/or replace.

Airbus has a similar alloy, Ti-5Al-5Mo-5V-3Cr-1Zr, which is also planned for use at the 1100 MPa strength level, again, to achieve better damage-tolerant properties. Their first application will be for fuse pins attaching the pylon to the wing on the A-380. The influence of thermomechanical processing on microstructure was discussed by Panter et al. (Ref 10) in this symposium.

The attractive properties combination achieved with this β heat treatment led to consideration of the alloy for castings also, as castings are obviously β-processed. A study was initiated with Howmet, and very attractive casting properties were achieved (Ref 11). The typical Ti-6Al-4V values were derived from the Howmet database. The static tensile properties are illustrated in Table 1. Fracture toughness from 93 to 104 MPa√m (85–94 ksi√ in.) was obtained. While these values were invalid due to specimen thickness, they are very encouraging.

The unnotched fatigue properties were also very attractive, as can be seen in Fig. 3. The Ti-5553 exhibits about a 60% improvement in the 10^7 cycle runout stress in comparison to that of Ti-6Al-4V castings. This improvement is attributed to the higher strength in conjunction with the excellent ductility (note that the Ti-5553 alloy has the same ductility as the Ti-6Al-4V castings with a 27% higher strength). The alloy was not quite as castable as Ti-6Al-4V; it had castability similar to that of Ti-6Al-2Sn-4Zr-2Mo and Ti-15V-3Cr-3Al-3Sn, both of which are production casting alloys.

An area that the authors have pursued for at least 20 years, which now appears to be achievable, is a high-strength titanium fastener. The goal has been to replace steel fasteners with a minimum tensile strength of 1380 MPa (200 ksi) and a minimum shear strength of 760 MPa (110 ksi). In addition, there is a fatigue criterion that needs to be met. Several β and near-β alloys have been studied, but the shear strength did not meet the goals, the threads could not be rolled, or they could not meet the fatigue requirements. SPS can meet these goals, at least up to fastener diameter sizes of 16 mm (0.625 in.) using the β-C alloy and special proprietary processing developed by SPS (Ref 12, 13). This product is referred to as SPS M761. It has been presented as a bolt material that is capable of meeting an 1100 MPa (160 ksi) tensile strength requirement. The data indicated that at least up to a 16 mm bolt diameter the material could meet the higher tensile, shear, and fatigue properties desired.

In addition, TiPro, a company that is devoted to titanium applications in the automotive aftermarket, has also developed an alloy that is apparently capable of meeting these requirements. Bania (Ref 14) developed this for the automotive aftermarket, and it seems to meet our requirements. The alloy is referred to as Ti-200, with the 200 referring to the tensile strength capability in ksi.

It is the authors' understanding that Airbus is also working on the development of high-strength titanium fasteners.

5. Summary

The use of β and near-β alloys seems to be on the gradual increase. These alloys are even beginning to be used by the regional and commuter aircraft manufacturers, although to a very limited degree at this stage. The major usage of this alloy system since the SR-71 has occurred on the B-1B bomber on the military side and on the Boeing 777 on the commercial side. Ti-15V-3Cr-3Al-3Sn sheet was used for nacelle and empennage structure on the B-1B bomber. On the 777, the major β alloy usage was in Ti-10V-2Fe-3Al forgings, primarily for landing gear structure. β21S was also introduced on this aircraft. The use of β-21S was a major breakthrough in that β alloys were never considered appropriate for elevated temperature applications due to their generally poor creep and oxidation resistance. These inherent shortcomings were overcome with this alloy. Although the higher cost of these alloys has been a factor in their rate of application, most of the applications have been driven by increased performance, and this will probably continue to be the case.

Another new development showing some promise is high-strength titanium fasteners using β alloys. Many high-strength fastener studies have been conducted over the years, but in every case the material could not meet the tensile strength, shear strength, and/or fatigue requirements. It appears that this problem is about to be overcome, as was discussed at this symposium.

There is yet another new development in this alloy system that is being developed by both Boeing and Airbus in cooperative efforts with VSMPO: the use of β alloys for damage-tolerant applications. Up to now, these alloys have only been used for static strength-designed parts due to the poor fracture toughness and fatigue crack growth characteristics. Both OEMs are studying a lower-strength condition that could provide satisfactory damage tolerance-type properties. Fracture properties would be improved when the material is used at a lower strength. A minimum fracture toughness of 77 MPa√m could be achieved, which is comparable to the high end of the spectrum for mill-annealed standard grade Ti-6Al-4V.

It is anticipated that the use of β alloys for aircraft will continue to expand, with gradual increases in utilization. The primary driver for the use of these alloys will continue to be improved performance, although there will be cases in which β alloys will offer economic advantages. An example of this could be Ti-15V-3Cr-3Al-3Sn strip in place of Ti-6Al-4V sheet product. The Ti-15V-3Cr-3Al-3Sn offers higher properties and lower cost for the lighter gages, and is strip-producible.

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